# Spectroscopic measurements of flow and ion temperature at SSX

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## 1. Introduction

- Ideal MHD postulates that plasma resistivity is zero, such that Ohm's Law for the plasma is

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = 0$$

- Ideal MHD predicts that magnetic field lines should be "frozen in" to the plasma
- Magnetic reconnection occurs when a large field gradient results in a breakdown of ideal MHD

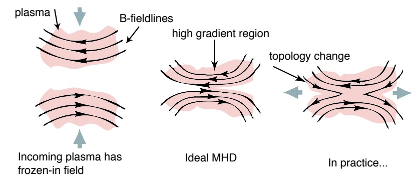


**Figure 1:** *Sweet-Parker picture of 2D magnetic reconnection.*

- **B** consumed during reconnection; energy density $B^2/2\mu_0$ of reconnected field converted to flow and heating
- Reconnection known to be complex, 3D process
- Simplest models inadequate; Sweet-Parker normalized reconnection rate $1/\sqrt{S}$ orders of magnitude too slow
- Magnetic reconnection thought to be involved in numerous astrophysical phenomena, including the heating of the solar corona

## 2. The Swarthmore Spheromak Experiment

- The Swarthmore Spheromak Experiment (SSX) studies magnetic reconnection by merging co- and counter-helicity spheromaks
- Spheromaks are toroidal plasma configurations with both poloidal and toroidal magnetic fields
- Spheromaks are an example of a force-free Grad-Shafranov equilibrium, with a pressure balance between kinetic and magnetic pressure
- Typical plasma parameters in SSX include electron density $n_e \sim 10^{15}$ cm$^{-3}$, temperature $T_i + T_e \sim 30$ eV, magnetic fields $|B| \sim 0.1$ T, $v_{\text{Alfvèn}} \sim 6$ cm/$\mu$s, and Lundquist number $S \sim 1000$.

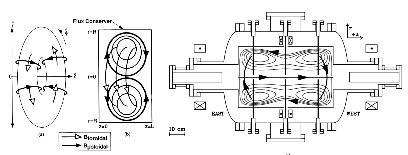


**Figure 2:** *a) & b): Two views of the geometry and fields of a spheromak. c): Overview of SSX chamber*

- Newly constructed high-resolution ion doppler spectroscopy (IDS) system allows better measurements of chord-integrated flows and ion temperatures
- IDS system observes spectral light emitted by impurity ions in the SSX hydrogen plasma
- The wavelength of light coming from plasma that is moving towards or away from the observer at speed $v$ is Doppler shifted by $\Delta\lambda$, where

$$\Delta\lambda = \lambda_0 \frac{v}{c}$$

and $\lambda_0$ is the nominal wavelength of the light

- Assuming a Maxwellian velocity distribution, the lineshape is Gaussian with half-width

$$\Delta\lambda_{\text{FWHM}} = \frac{2\lambda_0}{c}\sqrt{\frac{2kT_i \ln 2}{m}}$$

where $m$ is the mass of the emitting ions

## 3. The IDS System

- Collection optics select 1 of 10 chords through the plasma at midplane.
- Light travels through fiber optic to 2x magnifying input optics at entrance slit of 1.33 m Czerny-Turner monochromator with 316 grooves/mm echelle grating
- Magnifying exit optics increase the size of the image at the exit plane of the spectrometer $\sim$ 4x.
- 32-channel photomultiplier tube (PMT) array detector gives submicrosecond time response, but has wide (1mm) pixel width
- Wide (1mm) pixel width of PMT array is compensated for by the exit optics and by observing at high spectral order

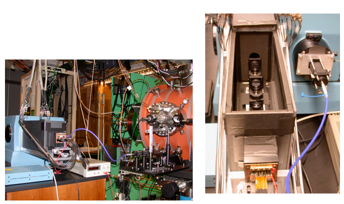

**Figure 3:** *Left: Photograph of SSX lab showing vacuum chamber, monochromator, and associated IDS optics. Right: Overhead view of spectrometer exit slit, magnifying optics, and PMT array. The fiber optic is visible at right.*

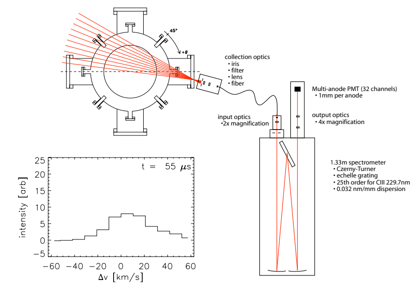


**Figure 4:** *Schematic of IDS system. Typical lineshape is shown at left.*

## 4. Results and Discussion

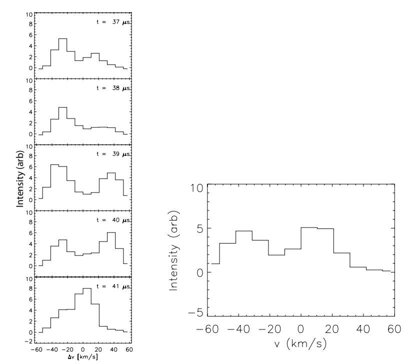


**Figure 5:** *227.9 nm CIII line during counter-helicity merging in two different shots. A time series is shown at left, while a single frame is shown at right. Velocities shown correspond to the Doppler shift of the emitting plasma.*

- 227.9 nm C III line observed at 25th order, with dispersion 0.008 nm/mm
- Instrument temperature $\sim$ 6 eV
- Only Doppler broadening is significant; other effects such as pressure broadening are negligible.
- Double-peaked lineshape shown above seen consistently during counter-helicity merging, when toroidal fields reconnect
- Bi-directional flows observed on the sun by spacecraft [1]
- Previous laboratory experiments observed broadened spectral lines but interpreted them as high ion temperatures [2]
- Broadening could be due to transient flows averaged out due to insufficient time resolution
- Abel inversions to determine radial profiles of velocity and ion temperature under way
- Assuming cylindrical symmetry, given some parameter $f(r)$, the quantity $F(y)$ that is measured along a chord of height $y$ from the center is given by

$$F(y) = 2\int_y^R \frac{f(r)r\,dr}{\sqrt{r^2 - y^2}}$$

- This equation can be solved for $f(r)$:

$$f(r) = -\frac{1}{\pi}\int_r^R \frac{dF}{dy}\frac{dy}{\sqrt{y^2 - r^2}}$$

- Because of derivative $\frac{dF}{dy}$, this equation cannot be directly applied to noisy data

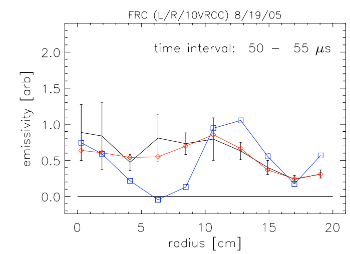


**Figure 6:** *Abel inversion of plasma emissivity. Blue line shows inverted plasma emissivity as a function of radius. Black line shows line-integrated emissivity as a function of chord height. Red line is a smoothed cubic spline interpolation to the data.*

- We have begun to do Abel inversions by interpolating $F(y)$ with cubic splines
- Radial profiles of plasma emmissivity calculated for dipole-trapped single spheromak shots and field-reversed configurations (FRC's) formed during counter-helicity merging
- Abel inversions of other plasma parameters ($v_{\text{radial}}$, $T_i$) are under way

## References

[1] D.E. Innes et al. Bi-directional plasma jets produced by magnetic reconnection on the Sun. *Nature*, 386 (1993), 811.

[2] Y. Ono et al. Experimental investigation of three-component magnetic reconnection by use of merging spheromaks and tokamaks. *Phys. Plasmas*, 4 (1997), 1953.